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Evaluating the Efficiency of Municipal Solid Waste Collection: Evidence from Taiwan

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Abstract

The management of substantial quantities of municipal solid waste (MSW) generated in urban areas presents significant challenges, primarily driven by rapid urbanization and population expansion. The Stochastic Frontier Analysis (SFA) model is adapted in this study to assess the collection efficiency of MSW in Taiwan's 22 counties and cities between 2010 and 2022, emphasizing the 2006 implementation of "mandatory waste sorting" policy. Results show noteworthy discrepancies in collection efficiency based on location, as distant island regions demonstrate lower efficiency owing to geographical location and resource limitations. Taipei and New Taipei City recycle very efficiently due to the success of the “pay-as-you-throw” policy, while the collection of general and kitchen wastes has become a challenge. The results provide empirical basis for enhancing waste management systems, fostering sustainable resource utilization, as well as supplying practical references for regions seeking to be more circular in nature.

Keywords: Municipal Solid Waste (MSW); Waste Collection Efficiency; Stochastic Frontier Analysis (SFA); Mandatory Waste Sorting Policy

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1. Introduction

The generation and complexity of municipal solid waste (MSW) are increasing with economic development, urbanization, and population growth. If not properly managed, MSW creates further hurdles in management and treatment, aside from contributing to environmental degradation and health risks (Gupta, Yadav, & Kumar, 2015). According to the *Global Waste Management Outlook 2024* issued by the United Nations Environment Programme (UNEP) and the International Solid Waste Association, the total volume of municipal solid waste in cities will increase from 2.3 billion tons in 2023 to 3.8 billion tons by 2050. Hence, effective management of municipal solid waste has become an urgent issue.

Municipal solid waste management involves recycling, incineration, waste-to-energy conversion, composting, and landfilling (Nanda & Berruti, 2021). Waste management practices are not mainly ineffective because they are poorly designed, but rather due to the lack of manpower, resources, and technology required to implement effective waste treatment, transportation, and disposal strategies. Therefore, an action plan should be designed with improved management strategies (Kumar et al., 2009). In addition, sustainable methods such as recycling, composting, and organic waste valorization should be emphasized alongside conventional options like landfilling and incineration. These techniques not only minimize waste but also help recover valuable resources. As waste collection stands as an essential process, this study draws attention to the effectiveness of municipal solid waste collection.

Recent studies on municipal solid waste management and collection service efficiency have focused on Italy, Spain, China, and Mexico (Guerrini et al., 2017; Campos-Alba et al., 2021; Fan et al., 2020; Salazar-Adams, 2021). Although these studies provide useful insights, only a few analyze the collection efficiency of different waste fraction types in sufficient detail. Research in this field has become especially relevant with the rise of the circular economy.

Since 2006, Taiwan has enforced a mandatory waste sorting policy requiring citizens to classify their trash into *general waste*, *recyclables*, and *kitchen waste* before disposal. This measure is intended to enhance the recycling rate and reduce environmental pollution. Yet, despite being in place for many years, there has been no systematic study examining the policy's collection efficiency.

This study examines whether the policy was effective by modeling municipal waste collection service efficiency using a Stochastic Frontier Analysis (SFA) model over the period 2010-2022 across 22 counties and cities in Taiwan. It also explores operational environmental factors that may affect efficiency. This research augments the existing literature and provides empirical evidence for decision-makers to improve solid waste management strategies and sustainable resource utilization.

This study is valuable in assessing the approaches adopted by Taiwanese counties and cities to promote and incentivize (or not) the implementation of the waste sorting policy, and in analyzing the degree of efficiency in sorting and collecting the three waste categories. First, the study analyzes the waste collection efficiency faced by different local governments during policy implementation, summarizing their adaptation strategies and outcomes. Second, the study uses the distinct sorting and collection characteristics of different waste types (i.e., general waste, recyclables, and kitchen waste) to explore the key influencing factors of sorting and collection efficiency and identify areas for improvement.

This work contributes meaningful knowledge on how to improve waste sorting and collection systems to maximize waste reduction and ultimately provide a stronger scientific rather than anecdotal basis for future policymaking. Through these comprehensive analyses, the research aims to serve as a reference for other countries and regions, promote the wider application of circular economy practices worldwide, and advance sustainable resource utilization and environmental protection.

2. Literature Review

Municipal solid waste (MSW) collection represents a substantial component of municipal expenditure, and its efficiency is shaped by multiple intersecting determinants. Existing studies indicate that operational inputs, socioeconomic conditions, and demographic structures play essential roles in explaining variations in MSW collection performance across regions.

2.1 Operational Inputs (manpower, cost, and equipment)

Operational resources form the foundational drivers of MSW collection efficiency. Financial inputs, in particular, have been repeatedly identified as a critical factor. Fan et al. (2020) demonstrated that in China, limited budgetary allocation and inefficient financial planning constrain operational performance, with a reported stochastic frontier efficiency of only 0.372, which indicates considerable potential for improvement. Consistent with this finding, Sulemana et al. (2020) emphasized that operating expenditure, especially fuel costs, significantly affects efficiency outcomes in Ghana, suggesting that effective cost management is indispensable for operational improvement.

Human resources also play a significant role in MSW collection efficiency. Chen and Chen (2012) found that service providers operating under a private ownership private operation (POPO) model achieved the best technical efficiency compared with other operational models, possibly because they had allocated their human resources more effectively. Teixeira et al. and Freeman et al. (2014) highlighted the need to monitor and regularly assess MSW collection systems, as such evaluations can identify strengths and weaknesses in human resource allocation and assist with strategic planning and decision-making.

Investment in equipment represents another important consideration. Llanquileo-Melgarejo et al. noted that selective collection and recycling systems demand investments in equipment and infrastructure, and such investments can significantly improve efficiency and the ecological advantages of MSW management (Luthra et al., 2021). Similarly, Guerrini et al. (2017) found in their study in Italy that collection methods (such as curbside or street-bin systems) and the volume of waste per load significantly impact cost efficiency, reflecting the effective use of equipment.

2.2 Contextual and Socioeconomic Determinants (economic, social, and demographic factors)

Beyond operational capacities, broader socioeconomic and demographic conditions shape MSW collection efficiency. Economic development may exert contradictory effects: while financial independence and tourism-related revenue have been shown to improve efficiency (Campos-Alba et al., 2021), Fan et al. (2020) reported that per capita GDP negatively correlates with efficiency in some contexts, suggesting that economic growth alone does not guarantee operational improvement and may even increase consumption-driven waste generation.

Social structure also matters. Romano and Molinos-Senante (2020) reported that younger residents contribute to higher ecological efficiency, demonstrating the influence of social structure. Rada et al. (2014) found that although tourism may reduce efficiency, it has a significant impact on selective MSW collection in Italy, reflecting a complex interaction between tourism and waste management.

Demographic factors are equally crucial. Based on Fan et al. (2020), demographic characteristics such as the proportion of the population between ages 15 and 64 significantly affect collection efficiency, meaning that shifts in population structure may increase or decrease MSW efficiency. Delgado-Antequera et al. (2021) also concluded that demographic characteristics, such as municipality size, service population, and population density, markedly influence ecological efficiency.

2.3 Synthesis and research gap

The efficiency of municipal solid waste (MSW) collection is shaped by a complex interplay of factors. Operational inputs-such as funding, workforce allocation, and equipment-form the fundamental basis of system functionality, while broader contextual conditions, including economic development, social structure, and demographic composition, influence efficiency outcomes to varying degrees. These dimensions interact to determine the overall performance of local MSW management systems. Therefore, enhancing MSW collection efficiency and advancing sustainable waste governance require policy and operational strategies that reflect local demographic, economic, and institutional contexts.

Despite valuable contributions from existing research, several notable gaps remain. Most previous studies have treated MSW as a single aggregated output, rather than differentiating among waste streams such as general waste, recyclables, and kitchen waste, which differ in policy mechanisms, operational procedures, and environmental implications. As a result, the heterogeneous efficiency characteristics across waste categories remain insufficiently examined. Moreover, although Taiwan has implemented mandatory waste sorting for nearly two decades and has achieved international recognition for waste reduction and recycling, empirical research employing longitudinal data and analyzing efficiency by waste category remains scarce.

In response, this study seeks to address these research gaps by incorporating a more context-sensitive and policy-relevant analytical perspective. By doing so, the study aims to generate evidence-based insights to support policymaking and deepen the understanding of MSW collection efficiency within the broader framework of circular economy transition and sustainable governance. Several input variables can affect the performance of municipal solid waste collection systems, including funding, human resources, and equipment. Economic, social, and demographic variables also influence the efficiency and effectiveness of MSW management to varying degrees. These factors interact with one another and collectively shape the overall performance of municipal solid waste management. Hence, to improve MSW collection efficiency and achieve sustainable waste management, regions must adopt appropriate policies and strategies tailored to their specific characteristics and requirements.

3. Data and Methodology

3.1 Sample Period And Data Sources

The sample period for this study spans from 2010 to 2021 and covers all 22 counties and cities in Taiwan, resulting in a total of 264 observations. By including every major administrative region, ranging from northern metropolitan areas to central, southern, and eastern counties as well as offshore islands, the sample provides comprehensive geographic coverage and can reasonably represent the overall Taiwan population. Data were obtained from National Statistics Taiwan (https://eng.stat.gov.tw/ Default.aspx).

3.2 Variable Specification

According to the characteristics of the SFA model, the output variable in this study uses the amount of MSW collected as the measurement. The input variables include the number of collection personnel, annual MSW collection investment, and number of garbage trucks, representing labor, capital investment, and physical resources, respectively. In addition, this study not only analyzes the average value of the total amount of MSW but also classifies MSW into three categories: "general waste," "recyclables," and "kitchen waste," and evaluates the input variables based on these categories. The descriptive statistics of the input-output variables of MSW collection services are shown in Table 1.

Table 1. Descriptive statistics of input-output variables in MSW collection services.

Variable name	Variable meaning	Observation number	Average value	Standard deviation	Maximum value	Minimum value
Y	The volume of MSW collection services (tons)	264	382,049	387,379	1,565,718	6,035
Y_GW	The volume of general waste collection services (tons)	264	165,537	161,176	684,982	1,926
Y_R	The volume of recyclables collection services (tons)	264	187,054	204,535	938,512	2,169
Y_KW	The volume of kitchen waste collection services (tons)	264	29,459	35,257	185,949	1,183
L	The number of people engaging in the MSW collection services	264	1,526	1,774	6,807	79
L_GW	The number of people engaging in the general waste collection services	264	825	958	4210	19
L_R	The number of people engaging in the recyclables collection services	264	533	602	2519	13
L_KW	The number of people engaging in the kitchen waste collection services	264	169	270	1349	15
K	The final accounts of expenditure of MSW collection services (thousand NT$)	264	1,421,888	1,779,259	7,887,829	6,456
K_GW	The final accounts of expenditure of general waste collection services (thousand NT$)	264	599,541	689,348	3,163,720	2,490
K_R	The final accounts of expenditure of recyclables collection services (thousand NT$)	264	704,460	947,522	4,884,236	2,253
K_KW	The final accounts of expenditure of kitchen	264	116,887	186,247	1,050,118	1,544

Variable name	Variable meaning	Observation number	Average value	Standard deviation	Maximum value	Minimum value
	waste collection services (thousand NT$)					
M	The number of vehicles and equipment for collecting MSW (unit)	264	685	640	3,054	30
M_GG	The number of vehicles and equipment for collecting general garbage (unit)	264	391	349	1657	11
M_R	The number of vehicles and equipment for collecting recyclables (unit)	264	220	212	1055	10
M_KW	The number of vehicles and equipment for collecting kitchen waste (unit)	264	74	94.	544	8

Notes:

1. The raw data for Y (including Y_GW, Y_R, Y_KW), L (including L_GW, L_R), K, and M (including M_GW, M_R) are all downloaded from the National Statistics Taiwan website (https://eng.stat.gov.tw/Default.aspx).
2. Since the data for L include both direct and indirect labor, while L_GW and L_R contain only direct labor, this study first allocates the indirect labor proportionally to L_GW and L_R. Furthermore, in Taiwan, kitchen waste is collected together with general garbage; therefore, this study recalculates L_GW and L_KW based on the collected weights (i.e., Y_GW and Y_KW).
3. Since there is no data for K_GW, K_R, K_KW, this study allocates the final accounts of expenditure based on the output of three categories of MSW (i.e., Y_GW, Y_R, Y_KW), thereby calculating the annual expenditure for K_GW, K_R, and K_KW respectively.
4. Since there is no data for M_KW, but as previously mentioned, kitchen waste is collected together with general garbage, this study uses the data from Y_GG and Y_KW to recalculate M_GW and M_KW.

Moreover, as previously noted in the literature review, municipal solid waste (MSW) collection services are also affected by socioeconomic characteristics, demographic characteristics, geographical characteristics, among other factors, according to several scholars. Based on previous studies and the availability of data, this research selected three variables to represent these aspects: per capita disposable income of the population, the proportion of the population aged 15-64, and population density. Descriptive statistics for these three inferred influencing factors are provided in Table 2.

Table 2. Descriptive statistics of explanatory variables influencing MSW collection services.

Variable name	Variable meaning	Observation number	Average value	Standard deviation	Maximum value	Minimum value
A	Per capita disposable income (Million NTS/person)	264	0.306	0.055	0.520	0.205
B	Proportion of population aged 15-64	264	0.728	0.784	0.671	0.021
C	Population density (Thousand population per square kilometer)	264	1.523	9.952	0.061	2.175

3.3 SFA (Stochastic Frontier Analysis)

This study applies Stochastic Frontier Analysis (SFA), an econometric approach commonly used to assess the efficiency of firms or production units. The rationale for adopting SFA lies in its statistical advantages and methodological suitability for efficiency evaluation, which make it more appropriate for this study compared with non-parametric methods such as Data Envelopment Analysis (DEA). According to Meeusen and van den Broeck (1977) and Aigner et al. (1977), SFA is a parametric efficiency estimation method that allows for the explicit specification of a cost or production function while simultaneously accounting for unavoidable random disturbances in real-world operations, such as policy variations, geographical constraints, and resource heterogeneity.

Unlike non-parametric approaches that treat all deviations from the efficiency frontier solely as managerial inefficiency, SFA decomposes the error term into a stochastic error component and a technical inefficiency component. This structure enables the model to distinguish between uncontrollable environmental factors and true inefficiency, thereby reducing bias in efficiency estimation and enhancing the robustness and interpretability of the results.

The analytical framework of this study is based on the stochastic frontier production and inefficiency effects model developed by Battese and Coelli (1995). Incorporating exogenous variables into the inefficiency component to examine their influence on technical efficiency, the empirical model used in this study is specified as follows:

$$ln(y_{it}) = \beta_0 + \beta_1 ln(L_{it}) + \beta_2 \ln(K_{it}) + \beta_3 \ln(M_{it}) + \nu_i - u_i \qquad (1)$$

where y_{it} represents the output of unit i at time t, L_{it} represents labor input, K_{it} represents capital input, M_{it} represents other resources or equipment input, and ν_{it} is the random error term capturing stochastic variations, and u_{it} is the technical inefficiency term reflecting inefficiency in the production process.

The SFA model includes a random error component that allows for variability in output which cannot be attributed to measurement errors, external environmental changes, or other stochastic factors. In addition to this random error term, the SFA framework also includes an inefficiency term. This term measures the distance of production units from the best practice frontier and, therefore, represents the degree of technical efficiency loss. The parameters of the production frontier function and the distribution associated with inefficiency can be estimated simultaneously using statistical methods such as maximum likelihood estimation.

The inefficiency function specifies how technical inefficiency is affected by a range of exogenous variables, which may include economic, social, or environmental factors. The inefficiency function is expressed as follows:

$$m_{\{it\}} = \delta_0 + \delta_1 A_{\{it\}} + \delta_2 B_{\{it\}} + \delta_3 C_{\{it\}} + \omega_{\{it\}} \qquad (2a)$$

$$m_{\{it\}} = z_{\{it\}} \qquad (2b)$$

where $m_{\{it\}}$ is the inefficiency term, $z_{\{it\}}$ is a vector of exogenous variables affecting inefficiency, δ is a vector of corresponding parameters, $A_{\{it\}}, B_{\{it\}}, C_{\{it\}}$ represent specific influencing factors and $\omega_{\{it\}}$ is the random error term.

4. Empirical Results

4.1 Results of MSW collection efficiency

Using the SFA method and Frontier 4.1 software, this study evaluates the MSW collection efficiency in 22 counties and cities in Taiwan over a 12-year period (2010 to 2021). Furthermore, this study investigates the collection efficiency of various categories of MSW. The empirical results for total MSW (column 2), general waste, recyclables, and kitchen waste are shown in Table 3.

Table 3. Parameter estimation results of SFA model in analyzing the efficiency of MSW collection services.

	MSW			General waste			Recyclables			Kitchen waste		
Estimated parameters	Estimated coefficient	Standard deviation	*t*-test value	Estimated coefficient	Standard deviation	*t*-test value	Estimated coefficient	Standard deviation	*t*-test value	Estimated coefficient	Standard deviation	*t*-test value
β_0	4.352***	0.311	14.006	3.981***	0.271	14.715	2.395***	0.339	7.063	4.319***	0.255	16.944
$\beta_1(L)$	0.394***	0.061	6.513	0.708***	0.060	11.884	-0.084	0.055	-1.523	0.712***	0.063	11.300
β_2(K)	0.179***	0.046	3.927	0.165***	0.040	4.170	0.584***	0.047	12.421	0.171***	0.036	4.741
β_2(M)	0.495***	0.069	7.185	0.230***	0.067	3.447	0.504***	0.050	9.985	0.176***	0.063	2.799
δ_0	-25.247***	4.339	-5.818	-29.436***	4.360	-6.752	-11.219***	2.362	-4.751	-40.095***	2.922	-13.723
δ_1(A)	4.962***	0.836	5.934	8.061***	1.497	5.384	2.946***	1.076	2.738	11.245***	1.117	10.071
δ_2(B)	32.151***	5.576	5.766	35.806***	5.269	6.796	14.848***	2.895	5.128	48.335***	3.669	13.174
δ_3(C)	-0.131***	0.045	-2.922	0.163***	0.035	4.719	-0.279***	0.035	-7.993	0.201***	0.034	5.843
σ^2	0.139***	0.025	5.484	0.155***	0.034	4.623	0.158***	0.027	5.960	0.259***	0.030	8.586
γ	0.603***	0.092	6.537	0.799***	0.059	13.520	0.557***	0.098	5.666	0.894***	0.015	60.558
	Log likelihood value -25.406			Log likelihood value 4.562			Log likelihood value -81.045			Log likelihood value -4.482		
	LR unilateral testing 191.417			LR unilateral testing 215.885			LR unilateral testing 109.481			LR unilateral testing 239.687		
	Mean Efficiency = 83.98%			Mean Efficiency = 80.53%			Mean Efficiency = 72.73%			Mean Efficiency = 78.95%		

The estimated coefficients of the γ values in Table 3 for overall MSW, general waste, recyclables, and kitchen waste are 0.603, 0.799, 0.557, and 0.894, respectively, all falling between 0 and 1 and statistically significant at the 1% level. This indicates that the SFA model is suitable for this estimation. Furthermore, except for β1(L) under the recyclable category, all other parameters passed the 1% statistical significance test. This demonstrates that using the SFA model to analyze MSW collection efficiency in Taiwan is reliable and that the results are credible.

This study then investigates the influence of variables on collection efficiency. As shown in Table 3, the coefficients of per capita disposable income for total MSW, general waste, recyclable waste, and kitchen waste are 4.962, 8.061, 2.946, and 11.245, respectively. This indicates a negative impact of per capita disposable income on the efficiency of different types of MSW collection services. These findings are consistent with Simoes et al. (2012) and Fan et al. (2020), suggesting that inefficient allocation of resources may explain this relationship. For example, excessively dense waste collection points may appear convenient but result in redundant operational capacity and wasted resources. Similarly, excessively frequent collection schedules may increase operating and labor costs, ultimately reducing overall collection efficiency.

The estimated coefficients for the proportion of the population aged 15-64 for overall MSW, general waste, recyclables, and kitchen waste are 32.151, 35.806, 14.848, and 48.335, respectively. This indicates that this variable works in the opposite direction, reducing the efficiency of MSW collection services. This result is inconsistent with the findings of Rogge and Jaeger (2013) and Fan et al. (2020). The underlying reasons may be as follows:

First, as the share of the population aged 15-64 increases, this group tends to engage more in urban life and consumption activities, generating larger amounts and a wider variety of waste. Theoretically, this should increase the demand for and efficiency of waste collection. However, in practice, the growth of this population also increases the demand for other public services, including education, healthcare, and transportation. This may result in the allocation of additional resources to these sectors, ultimately leaving insufficient support for waste collection and processing and negatively affecting efficiency.

Additionally, a growing working-age population introduces further challenges. In areas with high population concentration, waste collection and management may become more complex, particularly under traffic congestion and insufficient public infrastructure-both of which may hinder waste collection vehicle operations. The pressure generated by population growth may also strain existing waste treatment systems, thereby reducing the efficiency of general collection operations.

In summary, although a higher proportion of the population aged 15-64 theoretically implies higher waste collection efficiency, in practice this effect is weakened by increased demands on other public services and resource allocation pressure-ultimately resulting in efficiency loss. Therefore, resource allocation among public service sectors in urban planning and management should be balanced so that waste collection systems do not face resource shortages or operational strain.

The third influencing factor is population density. As summarized in Table 3, the coefficients for overall MSW, general waste, recyclable waste, and kitchen waste are -0.131, 0.163, -0.279, and 0.201, respectively. This means that population density positively influences the efficiency of overall MSW and recyclable waste collection services but negatively affects the efficiency of general waste and kitchen waste collection services.

High population density areas have certain advantages for the efficiency of total MSW and recyclables collection because collection points are closer to each other, reducing driving time. Additionally, larger waste volumes at individual collection points contribute to improved operational efficiency (Callan & Thomas, 2001). Under these conditions, waste collection vehicles can complete more tasks in the same amount of time, significantly improving work efficiency and resource utilization.

However, high population density also creates operational challenges for general waste and kitchen waste collection services. First, severe traffic congestion, especially during peak hours, reduces collection vehicle operating speeds, delays collection schedules, and increases operational costs. Second, collection route optimization becomes more difficult. In densely populated regions, urban layouts tend to be complex and irregular, which challenges waste managers when planning optimal collection routes. Furthermore, higher population density increases total waste generation, putting pressure on treatment facility capacity. If processing capacity does not match waste production speed, bottlenecks may arise, further impairing overall collection and processing performance.

Despite these conclusions, it should be noted that high population density areas have distinct advantages and challenges depending on the type of waste collection method used. Therefore, it is essential in such regions to consider traffic management, route optimization, and facility capacity comprehensively and adjust operational strategies continuously to improve efficiency.

4.2 Results of relative collection efficiency across counties

This study analyzes the collection efficiency of various MSW types across counties and cities from 2010 to 2021, and the corresponding results are presented in Tables 4.1, 4.2, 4.3, and 4.4, respectively.

Table 4.1. The efficiency of MSW collection services in 22 counties and cities of Taiwan from 2010 to 2021.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Average
Keelung City	0.91	0.90	0.88	0.88	0.87	0.84	0.85	0.88	0.93	0.94	0.94	0.95	0.90
Taipei City,	0.92	0.92	0.91	0.92	0.93	0.93	0.93	0.94	0.96	0.96	0.96	0.96	0.94
New Taipei City	0.66	0.55	0.56	0.56	0.56	0.52	0.57	0.66	0.79	0.80	0.84	0.87	0.66
Taoyuan City	0.92	0.89	0.87	0.88	0.86	0.85	0.86	0.88	0.91	0.92	0.93	0.93	0.89
Hsinchu City	0.95	0.95	0.95	0.95	0.95	0.95	0.94	0.94	0.96	0.96	0.96	0.96	0.95
Hsinchu County	0.95	0.94	0.94	0.93	0.93	0.92	0.90	0.88	0.91	0.92	0.91	0.92	0.92
Miaoli County	0.94	0.93	0.92	0.92	0.91	0.95	0.93	0.94	0.94	0.94	0.93	0.94	0.93
Taichung City	0.88	0.85	0.85	0.84	0.79	0.80	0.78	0.80	0.89	0.89	0.89	0.91	0.85
Changhua County	0.96	0.95	0.94	0.94	0.93	0.93	0.93	0.94	0.95	0.95	0.95	0.96	0.94
Nantou County	0.94	0.93	0.92	0.92	0.92	0.92	0.92	0.91	0.92	0.93	0.93	0.94	0.92
Yunlin County	0.95	0.94	0.93	0.93	0.92	0.94	0.92	0.91	0.93	0.93	0.93	0.93	0.93
Chiayi City	0.96	0.96	0.95	0.94	0.94	0.95	0.94	0.95	0.96	0.96	0.96	0.96	0.95

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Average
Chiayi County	0.95	0.94	0.93	0.94	0.93	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
Tainan City	0.91	0.88	0.86	0.85	0.86	0.86	0.88	0.89	0.93	0.94	0.94	0.95	0.90
Kaohsiung City	0.87	0.86	0.82	0.82	0.82	0.80	0.85	0.87	0.92	0.93	0.94	0.95	0.87
Pingtung County	0.91	0.88	0.86	0.86	0.85	0.87	0.88	0.89	0.92	0.92	0.91	0.92	0.89
Taitung County	0.93	0.92	0.91	0.90	0.89	0.92	0.92	0.91	0.91	0.91	0.90	0.92	0.91
Hualien County	0.91	0.88	0.83	0.84	0.85	0.84	0.84	0.86	0.89	0.89	0.90	0.92	0.87
Yilan County	0.93	0.92	0.89	0.89	0.85	0.85	0.84	0.85	0.89	0.90	0.90	0.91	0.88
Penghu County	0.89	0.89	0.82	0.78	0.76	0.84	0.77	0.81	0.81	0.77	0.80	0.85	0.82
Kinmen County	0.45	0.38	0.31	0.29	0.29	0.27	0.29	0.29	0.26	0.26	0.27	0.26	0.30
Lienchiang County	0.38	0.36	0.33	0.27	0.28	0.33	0.33	0.26	0.27	0.32	0.28	0.26	0.30

Mean Efficiency = 83.98%

Table 4.2. The efficiency of general waste collection services in 22 counties and cities of Taiwan from 2010 to 2021.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Average
Keelung City	0.85	0.83	0.80	0.82	0.80	0.75	0.72	0.75	0.90	0.90	0.91	0.93	0.83
Taipei City,	0.36	0.37	0.30	0.30	0.31	0.32	0.31	0.29	0.39	0.42	0.41	0.39	0.35
New Taipei City	0.60	0.48	0.51	0.50	0.48	0.45	0.48	0.55	0.72	0.72	0.72	0.72	0.58
Taoyuan City	0.91	0.87	0.86	0.87	0.86	0.82	0.81	0.83	0.88	0.89	0.91	0.91	0.87
Hsinchu City	0.94	0.94	0.94	0.92	0.93	0.92	0.88	0.87	0.93	0.92	0.92	0.92	0.92
Hsinchu County	0.96	0.95	0.95	0.95	0.95	0.94	0.89	0.86	0.90	0.91	0.90	0.91	0.92
Miaoli County	0.95	0.94	0.94	0.93	0.92	0.95	0.93	0.93	0.94	0.93	0.92	0.93	0.93
Taichung City	0.88	0.86	0.88	0.86	0.79	0.81	0.75	0.75	0.91	0.88	0.86	0.89	0.84

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Average
Changhua County	0.97	0.96	0.95	0.95	0.94	0.94	0.93	0.94	0.96	0.96	0.96	0.96	0.95
Nantou County	0.96	0.96	0.95	0.96	0.95	0.96	0.94	0.94	0.95	0.95	0.94	0.95	0.95
Yunlin County	0.96	0.95	0.94	0.94	0.92	0.92	0.91	0.90	0.92	0.91	0.92	0.91	0.92
Chiayi City	0.95	0.94	0.91	0.90	0.88	0.89	0.86	0.90	0.95	0.94	0.92	0.92	0.91
Chiayi County	0.96	0.96	0.95	0.96	0.95	0.95	0.94	0.93	0.93	0.93	0.92	0.93	0.94
Tainan City	0.91	0.89	0.87	0.87	0.87	0.88	0.87	0.89	0.95	0.95	0.95	0.95	0.90
Kaohsiung City	0.85	0.86	0.78	0.78	0.75	0.69	0.75	0.76	0.89	0.90	0.91	0.89	0.82
Pingtung County	0.93	0.90	0.88	0.89	0.88	0.89	0.88	0.87	0.92	0.92	0.86	0.88	0.89
Taitung County	0.94	0.94	0.94	0.93	0.93	0.92	0.92	0.91	0.91	0.90	0.89	0.91	0.92
Hualien County	0.92	0.90	0.87	0.86	0.87	0.89	0.86	0.86	0.88	0.87	0.89	0.89	0.88
Yilan County	0.95	0.95	0.93	0.94	0.91	0.91	0.88	0.87	0.91	0.90	0.89	0.90	0.91
Penghu County	0.89	0.90	0.82	0.80	0.82	0.88	0.75	0.78	0.79	0.73	0.84	0.87	0.82
Kinmen County	0.43	0.35	0.31	0.32	0.32	0.29	0.32	0.31	0.26	0.24	0.24	0.23	0.30
Lienchiang County	0.42	0.37	0.39	0.31	0.30	0.32	0.28	0.26	0.26	0.45	0.41	0.35	0.34

Mean Efficiency = 80.53%

Table 4.3. The efficiency of recyclables collection services in 22 counties and cities of Taiwan from 2010 to 2021.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Average
Keelung City	0.90	0.90	0.88	0.90	0.89	0.82	0.81	0.85	0.90	0.91	0.92	0.93	0.88
Taipei City,	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.97	0.97	0.97	0.97	0.96
New Taipei City	0.66	0.55	0.56	0.56	0.52	0.49	0.52	0.58	0.66	0.67	0.69	0.74	0.60
Taoyuan City	0.85	0.80	0.77	0.79	0.74	0.74	0.76	0.79	0.82	0.84	0.86	0.85	0.80

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Average
Hsinchu City	0.92	0.93	0.92	0.92	0.93	0.92	0.91	0.91	0.93	0.93	0.93	0.92	0.92
Hsinchu County	0.84	0.81	0.80	0.83	0.81	0.84	0.71	0.69	0.74	0.71	0.72	0.74	0.77
Miaoli County	0.77	0.75	0.73	0.69	0.68	0.93	0.83	0.84	0.85	0.83	0.73	0.78	0.78
Taichung City	0.72	0.77	0.77	0.79	0.68	0.67	0.65	0.67	0.76	0.75	0.77	0.83	0.74
Changhua County	0.88	0.87	0.86	0.86	0.84	0.83	0.82	0.86	0.90	0.89	0.89	0.90	0.87
Nantou County	0.76	0.74	0.72	0.73	0.74	0.75	0.70	0.68	0.70	0.68	0.70	0.74	0.72
Yunlin County	0.81	0.75	0.75	0.74	0.72	0.82	0.73	0.71	0.77	0.73	0.76	0.74	0.75
Chiayi City	0.94	0.93	0.92	0.92	0.92	0.92	0.92	0.93	0.94	0.94	0.93	0.94	0.93
Chiayi County	0.78	0.77	0.74	0.76	0.78	0.85	0.84	0.84	0.85	0.82	0.80	0.82	0.80
Tainan City	0.79	0.73	0.71	0.71	0.72	0.69	0.73	0.74	0.83	0.85	0.85	0.91	0.77
Kaohsiung City	0.79	0.77	0.75	0.75	0.75	0.69	0.76	0.79	0.86	0.88	0.89	0.90	0.80
Pingtung County	0.69	0.66	0.63	0.65	0.65	0.69	0.70	0.72	0.77	0.76	0.73	0.76	0.70
Taitung County	0.76	0.64	0.68	0.65	0.65	0.74	0.75	0.73	0.72	0.65	0.63	0.67	0.69
Hualien County	0.69	0.65	0.57	0.59	0.60	0.59	0.62	0.67	0.71	0.58	0.64	0.67	0.63
Yilan County	0.80	0.78	0.71	0.69	0.56	0.56	0.56	0.59	0.64	0.64	0.62	0.66	0.65
Penghu County	0.66	0.67	0.58	0.54	0.53	0.64	0.55	0.59	0.59	0.48	0.46	0.50	0.56
Kinmen County	0.38	0.34	0.30	0.32	0.33	0.31	0.34	0.34	0.31	0.28	0.30	0.28	0.32
Lienchiang County	0.52	0.50	0.42	0.29	0.35	0.42	0.39	0.33	0.29	0.28	0.20	0.20	0.35

Mean Efficiency =72.73 %

Table 4.4. The efficiency of kitchen waste collection services in 22 counties and cities of Taiwan from 2010 to 2021.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Average
Keelung City	0.84	0.82	0.79	0.82	0.81	0.74	0.71	0.74	0.91	0.90	0.92	0.93	0.83
Taipei City,	0.37	0.37	0.29	0.29	0.30	0.31	0.29	0.26	0.36	0.40	0.38	0.36	0.33
New Taipei City	0.61	0.47	0.51	0.49	0.48	0.45	0.47	0.55	0.75	0.74	0.73	0.71	0.58
Taoyuan City	0.91	0.86	0.85	0.87	0.86	0.85	0.85	0.87	0.90	0.92	0.92	0.93	0.88
Hsinchu City	0.94	0.94	0.94	0.92	0.93	0.92	0.86	0.86	0.92	0.92	0.92	0.92	0.92
Hsinchu County	0.95	0.95	0.94	0.94	0.94	0.93	0.87	0.85	0.89	0.90	0.90	0.91	0.92
Miaoli County	0.94	0.93	0.92	0.91	0.91	0.93	0.91	0.92	0.92	0.91	0.89	0.92	0.92
Taichung City	0.87	0.86	0.89	0.87	0.81	0.84	0.78	0.77	0.93	0.91	0.87	0.90	0.86
Changhua County	0.96	0.96	0.95	0.95	0.94	0.94	0.93	0.94	0.96	0.96	0.96	0.96	0.95
Nantou County	0.95	0.95	0.95	0.95	0.95	0.95	0.93	0.93	0.94	0.94	0.94	0.94	0.94
Yunlin County	0.94	0.93	0.93	0.92	0.90	0.90	0.88	0.85	0.89	0.89	0.90	0.88	0.90
Chiayi City	0.94	0.93	0.89	0.88	0.86	0.86	0.83	0.88	0.95	0.94	0.91	0.92	0.90
Chiayi County	0.96	0.95	0.95	0.95	0.94	0.94	0.93	0.91	0.91	0.91	0.89	0.89	0.93
Tainan City	0.91	0.88	0.86	0.85	0.86	0.86	0.86	0.88	0.95	0.95	0.95	0.95	0.90
Kaohsiung City	0.86	0.87	0.78	0.78	0.74	0.68	0.73	0.74	0.89	0.91	0.92	0.90	0.82
Pingtung County	0.92	0.89	0.87	0.88	0.87	0.88	0.88	0.87	0.93	0.91	0.85	0.87	0.88
Taitung County	0.93	0.92	0.92	0.92	0.91	0.89	0.89	0.87	0.88	0.87	0.85	0.88	0.89
Hualien County	0.90	0.88	0.83	0.83	0.84	0.87	0.84	0.82	0.85	0.83	0.86	0.85	0.85
Yilan County	0.94	0.93	0.91	0.91	0.87	0.88	0.86	0.85	0.89	0.87	0.87	0.88	0.89
Penghu County	0.84	0.85	0.72	0.72	0.75	0.81	0.68	0.69	0.71	0.64	0.79	0.81	0.75
Kinmen County	0.37	0.30	0.27	0.29	0.30	0.27	0.30	0.28	0.22	0.20	0.20	0.18	0.26
Lienchiang County	0.35	0.30	0.31	0.25	0.24	0.25	0.21	0.20	0.20	0.37	0.34	0.29	0.28

Mean Efficiency =78.95 %

From Table 4.1, the overall average collection efficiency of MSW is 83.98%. Among these, Kinmen County and Lienchiang County—both outlying island counties-have an average efficiency of only 0.30, which is significantly lower than that of counties and cities on Taiwan's main island. This may be due to scale effects. Economies of scale can significantly influence waste collection efficiency. As collection volume increases, the average cost per transaction decreases, thereby improving operational efficiency and economic performance. However, outlying island areas generally generate less MSW, while required fixed inputs and operating costs remain, resulting in relatively lower waste collection efficiency in these regions.

In addition, the geographical location and transportation challenges of these outlying island counties may further affect collection efficiency. In such areas, the fixed cost of transporting and processing waste must be spread across a smaller total waste volume, further reducing efficiency. Based on these factors, it can be concluded that outlying island regions require greater policy support and resource allocation to improve MSW collection efficiency despite geographical and economic limitations. During peak tourism seasons, the population influx in these counties becomes significantly larger than the permanent resident population. The resulting surge in waste generation, combined with logistical challenges, further decreases overall efficiency. Temporary population surges and increased waste volumes place additional pressure on existing waste collection systems, stressing resource allocation. These circumstances require local governments to adopt more agile planning and operational strategies, especially to respond to seasonal changes and maintain waste management efficiency during peak tourism periods.

According to Table 4.2, the mean collection efficiency for general waste is 80.53%. Unexpectedly, the average efficiency of Taipei City and New Taipei City is only 0.35 and 0.58, respectively. This phenomenon may be associated with their garbage fee policies, as both Taipei City and New Taipei City have implemented the pay-as-you-throw (PAYT) system, while other counties and cities have not.

The PAYT policy aims to reduce waste generation and improve recycling rates by requiring residents to pay based on the amount of waste they produce, rather than rewarding how effectively they recycle or compost. As residents are charged for waste disposal, they are incentivized to sort and reduce their waste. Although this policy reduces the overall volume of municipal solid waste and enhances environmental benefits, the frequency of waste collection has not decreased correspondingly. As a result, transportation and labor costs remain largely unchanged, leading to lower collection efficiency.

Table 4.3 shows that the average collection efficiency for recyclables is 72.73%, which is lower than the efficiency observed in other MSW categories. This may indicate an area requiring further government attention and improvement. Comparing mean efficiencies across counties and cities reveals that Taipei City reaches as high as 0.96, demonstrating that the PAYT policy continues to be effective in waste management.

Lastly, Table 4.4 shows mean collection efficiencies of 0.33 and 0.58 for kitchen waste in Taipei City and New Taipei City, respectively. One possible explanation is that general waste and kitchen waste in Taiwan are transported and processed together using the same garbage trucks. As the frequency of waste collection has not decreased and the associated input costs have not been reduced, the resulting collection efficiency remains low.

5. Conclusions

This study evaluates the efficiency of municipal solid waste (MSW) collection in Taiwan under the mandatory waste sorting policy implemented in 2006. Using panel data from 22 counties and municipalities from 2010 to 2022 and applying a Stochastic Frontier Analysis (SFA) model, this research examines the operational efficiency of MSW collection and investigates the influence of socioeconomic and demographic variables. The results indicate substantial regional variation in efficiency, reflecting the interactive effects of policy design, geographic constraints, demographic structure, and administrative capacity. Overall, the findings provide empirical insights that help explain practical challenges in waste governance and identify areas requiring strategic improvement.

5.1 Theoretical Implications

The analysis demonstrates that MSW collection efficiency is shaped not by a single determinant but by the combined influence of operational inputs and contextual socioeconomic structures. High-density urban areas benefit from economies of scale in total MSW and recyclable collection, yet efficiency declines for general waste and kitchen waste due to traffic congestion, route complexity, and infrastructure capacity limits. Moreover, higher income levels and a larger proportion of older residents are associated with lower efficiency, implying potential misalignment between service needs and resource allocation.

A key theoretical contribution of this study is emphasizing the conceptual distinction between efficiency and effectiveness in evaluating waste governance outcomes. While efficiency reflects optimized allocation of inputs such as labor, equipment, and transportation, effectiveness determines whether policies achieve environmental objectives such as waste reduction and increased recycling rates. The PAYT system implemented in Taipei and New Taipei demonstrates high policy effectiveness but does not necessarily translate into higher collection efficiency when transportation frequency remains unchanged. This finding underscores the importance of integrating both dimensions when assessing policy performance.

5.2 Managerial and Policy Implications

Based on the results, several recommendations for policy and operational improvement are proposed. In remote and island regions such as Kinmen and Lienchiang, where scale limitations and logistics constraints hinder efficiency, more flexible collection models—such as demand-responsive scheduling, shared assets, or regionally coordinated operations—may reduce fixed operating costs and improve efficiency. In high-density metropolitan areas, incorporating smart route optimization, real-time fleet dispatching, and data-driven monitoring can mitigate congestion challenges and enhance resource utilization. In jurisdictions implementing PAYT, complementary adjustments such as modifying collection frequency, upgrading recycling infrastructure, or improving sorting mechanisms can ensure that efficiency gains align with policy effectiveness. Finally, population dynamics and seasonal fluctuations, particularly in tourism cities, should be integrated into planning, with seasonal or time-based operational strategies adopted to enhance system resilience.

5.3 Limitations and Future Research

This study has several limitations. First, the analysis is based on county-level data, which may mask intra-regional variations such as urban-rural differences or community-level behavior. Second, the research emphasizes efficiency evaluation and does not include governance performance indicators measuring policy effectiveness, such as waste reduction magnitude, sorting quality, or citizen participation. Future research could develop a dual-dimensional framework integrating efficiency and effectiveness to provide a more comprehensive governance assessment. Additionally, future studies may incorporate circular economy policies, smart governance technologies (e.g., AI-based dispatching, IoT sensing), or green infrastructure to assess their contributions to both operational efficiency and environmental outcomes.

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評估都市固體廢棄物清運效率：來自臺灣的實證證據

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摘要

都市地區所產生的大量都市固體廢棄物（MSW），在快速都市化與人口成長的推動下，已形成重大管理挑戰。本研究採用隨機邊界分析模型（Stochastic Frontier Analysis, SFA），評估臺灣地區 22 個縣市於 2010 至 2022 年間的廢棄物清運效率，並特別關注 2006 年實施的「垃圾強制分類」政策。研究結果顯示，不同地區的清運效率存在明顯差異，其中離島地區因地理位置與資源限制而呈現較低效率。臺北市與新北市在回收效率方面表現突出，主要歸功於「隨袋徵收」政策的成功；然而，一般垃圾與廚餘的清運則成為日益嚴峻的挑戰。本研究結果提供強而有力的實證基礎，以促進強化廢棄物管理系統，以及推動資源永續利用，並為致力於提升循環化發展的地區，提供具體的參考。

關鍵字：都市固體廢棄物（MSW）、廢棄物清運效率、隨機邊界分析（SFA）、垃圾強制分類政策

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